Available on CMS information server

CMS CR -2020/049

The Compact Muon Solenoid Experiment

Conference Report

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

08 February 2020 (v5, 01 September 2020)

Measurements and simulations of surface and bulk radiation damage effects in silicon detectors for the CMS Phase-2 Outer Tracker

Valentina Mariani for the CMS Collaboration

Abstract

In this work we address the effects of bulk and surface damages on detectors fabricated by Hamamatsu on standard float zone (FZ) p-type material with an active thickness of 290 μm or thinned to 240 μm. In order to disentangle the effects of the two main radiation damage mechanisms, ionization effects and atomic displacement, the structures underwent two types of radiation: X-ray with doses from 0.05 to 70 Mrad (SiO_2) and neutron in the range of $1-10 \times 10^{14}$ n_{eq}/cm^2 1 MeV equivalent. The combined surface and bulk damage could be investigated in structures that underwent both types of irradiation. A wide set of measurements has been carried out on the test structures for a complete characterization.

Presented at *HSTD12 12th International Hiroshima Symposium on the Development and Application of Semiconductor Tracking Detectors (HSTD12)*

Measurements of surface and bulk radiation damage effects in silicon detectors for Phase-2 CMS Outer Tracker [1]

Valentina Mariani[a], Francesco Moscatelli[a,b], Arianna Morozzi[a], Daniele Passeri[a,c], Serena Mattiazzo[d], Thomas Bergauer[e], Marko Dragicevic[e], Viktoria Hinger[e], Alexander Dierlamm[f], on behalf of the CMS Collaboration

[a] *INFN Perugia, Via Pascoli 1, Perugia, Italy*
[b] *CNR-IOM Perugia, Via Pascoli 1, Perugia, Italy*
[c] *University of Perugia, Via G. Duranti 93, Perugia, Italy*
[d] *University and INFN of Padova, via Marzolo 8, 35131 Padova, Italy*
[e] *HEPHY, Austrian Academy of Sciences, 1050 Wien, Austria*
[f] *Karlsuhe Institute of Tecnology, 76131 Karlsruhe, Germany*

Abstract

In this work we address the effects of bulk and surface damages on detectors fabricated by Hamamatsu on standard float zone (FZ) p-type material with an active thickness of 290 µm or thinned to 240 µm. In order to disentangle the effects of the two main radiation damage mechanisms, ionization effects and atomic displacement, the structures underwent two types of radiation: X-ray with doses from 0.05 to 70 Mrad (SiO_2) and neutron in the range of $1-10 \times 10^{14}$ n_{eq}/cm^2 1 MeV equivalent. The combined surface and bulk damage could be investigated in structures that underwent both types of irradiation. A wide set of measurements has been carried out on the test structures for a complete characterization.

Keywords: Models and simulations; Radiation damage to detector materials (solid state); Solid state detectors; Radiation-hard detectors

[1] Published in Nuclear Instruments and Methods in Physics Research Section A. https://doi.org/10.1016/j.nima.2020.164423

1. Introduction

During the High Luminosity (HL) era at the Large Hadron Collider (LHC), the tracking detector will be exposed to extremely high fluences. Values of about 2.2×10^{16} (1×10^{15}) 1 MeV n_{eq}/cm^2 are expected to be reached in the inner (outer) tracker of the CMS experiment. In this scenario the design of the new CMS tracker has to comply with stringent constraints, especially in terms of radiation hardness. For this reason, a deep understanding of the physics phenomena related to the surface and bulk radiation damage effects in the silicon sensors is of crucial importance.

In this work the radiation effects have been studied on detectors fabricated by Hamamatsu Photonics K.K. in Japan (HPK) on standard Float Zone (FZ) p-type material. The irradiation and measurement campaigns focused specifically on disentangling the effects of the two main radiation damage mechanisms, ionization effects and atomic displacement. The objective is to highlight potential weak points of the devices and then to devise radiation resistant solutions. The interface trap state density and the oxide charge can be extracted from standard test structures for each substrate before and after irradiation with X-rays aiming at the surface damage characterization. Neutron irradiations have also been performed to study the bulk effects. For some structures measurements have been carried out after both irradiations, allowing the combined surface and bulk damage to be investigated. In the next paragraphs the measurements will be presented together with a discussion of the obtained results.

2. Experimental Setup and Measurements

The measurements that will be discussed in this paper have been performed on dedicated p-type test structures fabricated by Hamamatsu. Two different sensor technologies, with an oxide thickness of 700nm, have been analysed: Float Zone with an active thickness of 290µm, indicated throughout the text as FZ290, and Float Zone with a thinned active thickness of 240 µm, indicated as FZth240. The comparison between the two different technologies allows underpinning any possible critical dependence on the thickness of the sensors that will be used to build the tracker for the HL-LHC upgrade.

In both cases the test structures include MOS capacitors, gated diodes, diodes and test structures to measure the interstrip resistance. The interdigitated gated diode, consists of 25 gate fingers (connected in a comb-like structure) having an 80 µm pitch. To evaluate the surface effects in terms of strip isolation, a simple two strip structure featuring double p-stop implant (with low peak doping concentration), 4 µm wide and separated by 6 µm has been used. The n+ strip width was 50 µm. The strip pitch was 120 µm. This structure is very similar to the latest real detector design.

The X-ray irradiations were carried out at the Department of Physics and Astronomy of the University of Padova (Italy) at room temperature and ambient humidity without bias polarization, with a continuous irradiation. The dose ranged from 0.05 to 70 Mrad in SiO_2, with an X-ray energy in the range of 8-40 keV. The X-ray spectrum emitted from the tube was additionally filtered for total dose tests by 0.15 mm aluminium in order to attenuate the low-energy (<8 keV) component [1]. The dose rate was 0.8 Mrad per hour (in SiO_2).

The neutron irradiations have been carried out in Ljubljana, at room temperature, at four different fluences from 1.5×10^{14} 1 MeV n_{eq}/cm^2 to 1×10^{15} 1 MeV n_{eq}/cm^2 reproducing the expected doses in the CMS outer tracker after collecting an integrated luminosity of $3000\,fb^{-1}$, corresponding to the whole HL-LHC expected data taking. To study the combination of the surface and bulk radiation damages, part of the test structures already irradiated with X-rays underwent neutron irradiation as well, obtaining four different combinations:

- 5 Mrad (SiO_2) + 1.5×10^{14} 1 MeV n_{eq}/cm^2
- 10 Mrad (SiO_2) + 3×10^{14} 1 MeV n_{eq}/cm^2
- 20 Mrad (SiO_2) + 6×10^{14} 1 MeV n_{eq}/cm^2
- 70 Mrad (SiO_2) + 1×10^{15} 1 MeV n_{eq}/cm^2

The experimental setup is based on a semi-automatic probe station, MPI TS2000 SE. The measurements have been carried out in the clean room of the INFN laboratory in Perugia (Italy), where dry nitrogen is pumped to have a relative humidity lower than 20%. Sensors irradiated with the X-ray have been measured at the temperatures of T = + 20°C and T = - 20°C, while for neutron-irradiated sensors only measurements at T = - 20°C have been performed. Sensore were annealed at T = 80°C for 10 minutes [2, 3]. Dry nitrogen is used to prevent condensation on the sensor surface when measures are carry out at T = - 20°C. Each measurement has been repeated at least three times to ensure its precision and repeatability.

Increasing ionizing X-ray radiation dose results in the increase of both interface traps and trapped-oxide charge. These parameters have been evaluated using specific methodologies (as described in [4]). The effective oxide charge density N_{EFF} is obtained from the flat-band voltage extrapolation derived from C-V measurements of MOS capacitors as in [4], while the interface trap states spectral densities D_{IT} and the integrated interface trap density N_{IT}, obtained integrating D_{IT} from the valence band to midgap, are determined by applying the capacitance High-Low frequency measurement method [4]. The surface recombination velocity s_0 is determined from I-V measurements on gated-diodes and it is found to be related to D_{IT} [5].

Current-Voltage (I-V) and Capacitance-Voltage (C-V) measurements have been carried out with a computer-controlled parametric system. More information about the setup and the measurements themselves can be found in [6].

3. Measurements

This work is based on [7], adding the bulk effect after the neutron irradiation to the surface radiation damage study. In this section the two measurements will be described in detail, together with the obtained results.

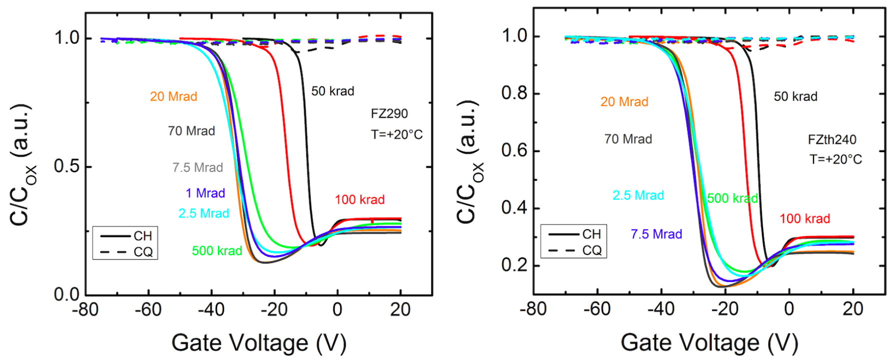


Figure 1: C-V characteristics of MOS capacitors at X-ray doses of 0.05, 0.1, 0.5, 2.5, 7.5, 20 and 70 Mrad(SiO_2) measured at T = +20°C for FZth240 on the left and FZ290 on the right. C_{OX} is the oxide capacitance, CH indicated the high-frequency capacitance and CQ the quasi-static capacitance.

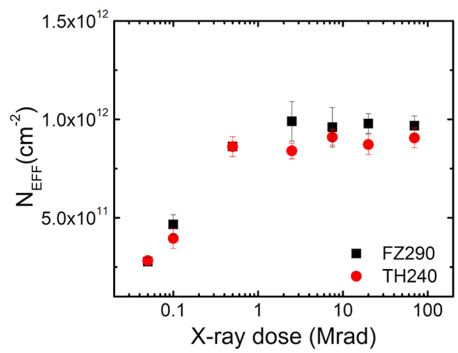
3.1. Surface radiation damage

The main goal of the measurement campaign was to extrapolate, for both technologies, the relevant parameters able to describe the surface damage effects to be included within the respective TCAD model.

In Figure 1 the C-V curves of the irradiated MOS are shown for FZth240 on the left and FZ290 on the right at different X-ray doses from 50 krad to 70 Mrad. A saturation of the flat band voltage (V_{FB}), calculated according to the flat-band capacitance method as in [4], is observed for doses higher than 1 Mrad (SiO_2).

The parameters N_{EFF} and N_{IT} have been thus extracted from these curves and reported in Figure 2 as a function of the radiation dose comparing FZth240 in red to FZ290 in black. A similar saturation effect at high doses is shown for the N_{EFF} and N_{IT} parameters.

An I-V characterization has been performed on the gated-diode after the X-ray irradiation, as shown in Figure 3 for different X-ray doses at two different temperatures T = + 20°C and T = - 20°C. The surface recombination velocity



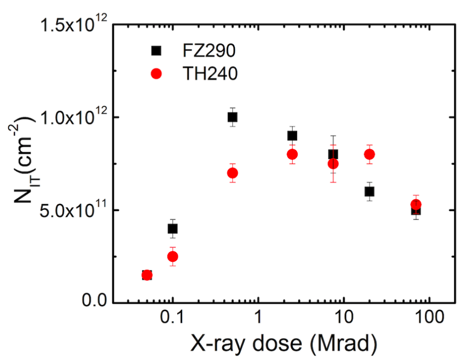


Figure 2: Effective oxide charge density N_{EFF} (top) and integrated interface trap density N_{IT} (bottom) as a function of the X-ray dose measured on FZ290 (black) and FZth240 (red) structure tests.

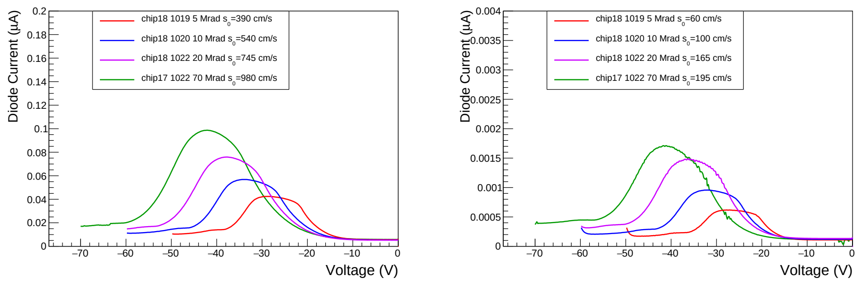


Figure 3: I-V characteristics of gated diodes at X-ray doses of 5, 10, 20 and 70 Mrad measured at T=+20°C (left) and T=-20°C (right).

s_0 has been evaluated for each measurement as

$$s_0 = \frac{I_{max} - I_{ave}}{e \cdot n_i \cdot A} \quad (1)$$

where I_{max} and I_{ave} are the maximum value and the average on the flat part of the right tail of the current respectively, e is the electron charge, n_i is the concentration of the charge carriers and A is the gate area. A strong dependence on the irradiation dose and temperature is observed. An increase of s_0 is shown as the X-ray dose increases, while it decreases significantly cooling the system from T = +20°C down to T= -20°C.

To complete the surface radiation damage discussion the interstrip resistance measurements are reported on Figure 4, again at two different temperatures T = ± 20°C. A strong dependence on the magnitude of the resistance measurement can be observed as an offset between the curves. Comparing the measured resistance for the same X-ray dose, a difference of about one order of magnitude between T = +20°C and T = -20°C is observed.

3.2. Bulk and surface radiation damages

As shown in Figure 5, the gated diode I-V characterization substantially changes in test structures for which neutron irradiations are combined to X-ray irradiations, in the configurations already discussed, with respect to the test structures irradiated with X-ray only (Figure 3), meaning that the bulk effect is

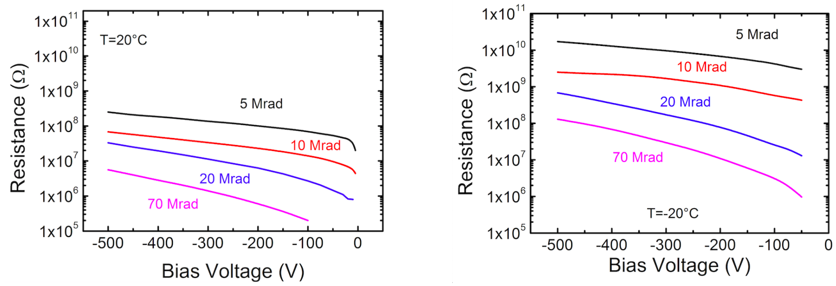


Figure 4: Interstrip resistance as a function of the bias voltage at X-ray doses of 5, 10, 20 and 70 Mrad measured at T=+20°C (left) and T=-20°C (right).

strongly affecting the I-V measurement. For the neutron irradiated devices temperature has been found to heavily affect the measurement due to an increase of bulk current. Three measurements per device have been performed and, to avoid significant variations in the electric response, the setup temperature has been kept between T=-20.1°C and T = -20.0°C. Even a small temperature fluctuation out of this range results in a no-negligible current variation of 10-15 %. The temperature also causes the current to decrease in the inverse region, for $V > 10$ V. As a result, when calculating s_0 as in Equation 1 some additional considerations are needed for the evaluation of I_{ave}. To enhance the real device response above the temperature effect, a linear fit has been performed on the right tail, so that the s_0 numerator is calculated as the difference between I_{max} and the value of the fit at the same voltage, as sketched in Figure 5. In addition, unlike the X-ray irradiated structure, in this case the variation in current between the inversion and the depletion value is quite small and more difficult to evaluate.

In Table 1 the measured s_0 values are compared for different doses. It can be seen that for a fixed X-ray dose, the s_0 parameter remains comparable within the uncertainties before and after the additional neutron irradiation.

Finally Figure 6 shows how the interstrip resistance measurements change with the additional neutron radiation, on the left for FZ290 and on the right for FZth240. No significative differences between the two technologies appear,

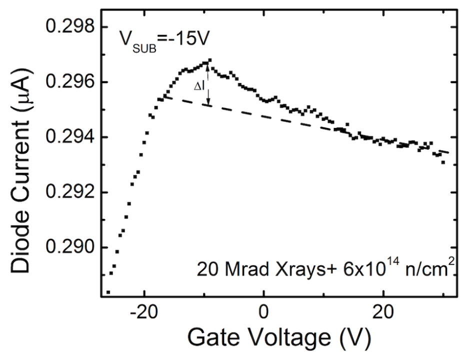


Figure 5: Measured I-V characteristics in gated diode after X-ray + neutron doses at T=-20°C.

Dose [Mrad]	ΔI [A]	s_0 [cm/s]	Dose [1 MeV n/cm^2+Mrad]	ΔI [A]	s_0 [cm/s]
5	5.07×10^{-10}	62	1.5×10^{14} + 5	4.50×10^{-10}	55 ± 10
10	8.36×10^{-10}	103	3×10^{14} + 10	9.86×10^{-10}	115 ± 30
20	1.35×10^{-9}	166	6×10^{14} + 20	1.45×10^{-9}	178 ± 10
70	1.59×10^{-9}	195	1×10^{15} + 70	1.65×10^{-9}	202 ± 17

Table 1: The surface recombination velocity s_0 values measured for different doses of X-ray only and X-ray combined to neutrons.

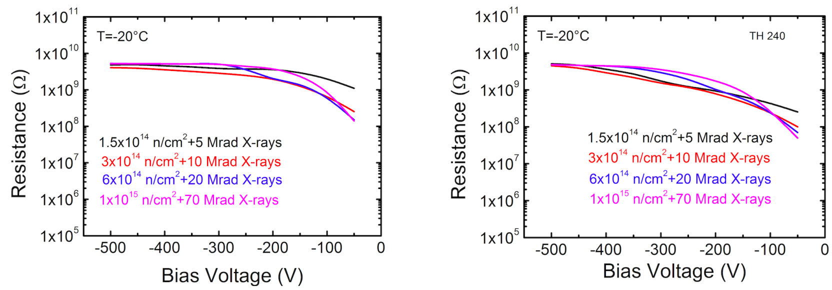


Figure 6: Interstrip resistance measurement as a function of the bias voltage at the four X-ray + neutron irradiation doses at T=-20°C, on the left for FZ290 and on the right for FZth240.

while a clear saturation effect is shown at high bias voltage values for both of them.

The bulk effect dominates and compensation effects are directly visible, as already shown in [8]. By introducing bulk defects, electrons are trapped near the surface, where an effective negative charge is built up. This fixed negative charge compensates the positive oxide charge in the surface, which leads to a suppression of the electron accumulation layer. We can conclude that strips remain highly isolated even after high fluences, comparable to the ones foreseen at the end of the HL-LHC.

4. Conclusion

In view of the upcoming CMS Outer Tracker upgrade for the High Luminosity phase of LHC, an intense characterization of silicon sensor started. The effects of the surface and bulk radiation damages have been studied by means of an extensive experimental measurement campaign. Two technologies of detectors fabricated by Hamamatsu on standard FZ p-type material with an oxide thickness of 700 nm have been studied: Float Zone with an active thickness of 290 µm (FZ290) and Float Zone with a thinned active thickness of 240 µm (FZth240). Both of them underwent two different irradiations, X-rays and neutrons, in order to disentangle ionization effects and atomic displacement. In general a similar behaviour between the two technologies has been observed and no weaknesses have been identified. Measurements after the neutron irradiations, performed according to the expected radiation exposure at the HL-LHC scenario, still show good performances. Surface recombination velocities s_0 have been measured after both irradiations and have been found to be compatible, within the uncertainties. Interstrip resistance measurements after the combination X-ray and neutron irradiations shows a compensation effect and demonstrates that strips remain highly isolated even after high fluences, comparable to the ones foreseen at the end of the HL-LHC. All the parameters measured in this campaign will be important input for the simulation tools, in order to provide a general radiation damage model.

[1] D. Bisello, et al., X-ray radiation source for total dose radiation studies, Radiation Physics and Chemistry vol. 71, pp. 713-715, 2004.

[2] J. Zhang, I. Pintilie, E. Fretwurst, R. Klanner, H. Perrey and J. Schwandt, Study of radiation damage induced by 12 keV X-rays in MOS structures built on high-resistivity n-type silicon, J. Synchroton Rad.19 (2012) 340-346.

[3] J. Zhang, et al., Study of X-ray radiation damage in silicon sensors Journal of Instr. 6 (2011) C11013.

[4] E. H. Nicollian and J. R. Brews, Hoboken, MOS (metal oxide semiconductor) physics and technology: Wiley, 1982, pp. 319-356.

[5] D. M. Fleetwood, S. T. Pantelides, R. D. Schrimpf, Oxide Traps, Border Traps and Interface Traps in SiO2, Defects in Microelectronic Materials and Devices, pp. 218-248. Boca Raton: CRC Press, 2009.

[6] F. Moscatelli et al., Effects of Interface Donor Trap States on Isolation Properties of Detectors Operating at High Luminosity LHC (HL-LHC), IEEE Trans. on Nucl. Sci. 64 (8) (2017) 2259-2267.

[7] F. Moscatelli et al., Measurements and simulations of surface radiation damage effects on IFX and HPK test structures, Nuclear Instruments and

Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment A 958 (2020) 162794

[8] Jan-Ole Gosewisch, Irradiation Studies of Charge Collection and Interstrip Resistance of Silicon Strip Sensors in the Course of the CMS Phase-2 Upgrade Master Thesis (2018)